

# USER'S GUIDE

## Demonstration of a Fractured Rock Geophysical Toolbox (FRGT) for Characterization and Monitoring of DNAPL Biodegradation in Fractured Rock Aquifers

ESTCP Project ER-201118

JANUARY 2016

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| <b>REPORT DOCUMENTATION PAGE</b>   |                    |                                   |                  |  | <i>Form Approved</i><br>OMB No. 0704-0188                       |              |              |    |   |                                     |   |  |  |  |
|--|--------------------|-----------------------------------|------------------|--|---|--------------|--------------|----|---|-------------------------------------|---|--|--|--|
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| <b>1. REPORT DATE (DD-MM-YYYY)</b><br>01/01/2016   |                    | <b>2. REPORT TYPE</b><br>Guidance |                  |  | <b>3. DATES COVERED (From - To)</b><br>July 2011 - January 2016 |              |              |    |   |                                     |   |  |  |  |
| <b>4. TITLE AND SUBTITLE</b><br>Demonstration of a Fractured Rock Geophysical Toolbox (FRGT) for Characterization and Monitoring of DNAPL Biodegradation in Fractured Rock Aquifers  |                    |                                   |                  | <b>5a. CONTRACT NUMBER</b><br>W912HQ-11-C-0027 |   |              |              |    |   |                                     |   |  |  |  |
|  |                    |                                   |                  | <b>5b. GRANT NUMBER</b>                        |   |              |              |    |   |                                     |   |  |  |  |
|  |                    |                                   |                  | <b>5c. PROGRAM ELEMENT NUMBER</b>              |   |              |              |    |   |                                     |   |  |  |  |
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|  |                    |                                   |                  | <b>5e. TASK NUMBER</b>                         |   |              |              |    |   |                                     |   |  |  |  |
|  |                    |                                   |                  | <b>5f. WORK UNIT NUMBER</b>                    |   |              |              |    |   |                                     |   |  |  |  |
| <b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b><br>Rutgers University, 101 Warren Street, Newark, NJ 07102<br>USGS, 12201 Sunrise Valley Drive, Reston, VA 20192<br>Pacific Northwest National Laboratory, 902 Battelle Blvd, Richland, WA 99352   |                    |                                   |                  |  | <b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>                 |              |              |    |   |                                     |   |  |  |  |
| <b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b><br>Environmental Security Technology Certification Program Program Office<br>4800 Mark Center Drive<br>Suite 17D03<br>Alexandria, VA 22350-3605   |                    |                                   |                  |  | <b>10. SPONSOR/MONITOR'S ACRONYM(S)</b><br>ESTCP                |              |              |    |   |                                     |   |  |  |  |
|  |                    |                                   |                  |  | <b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b>                   |              |              |    |   |                                     |   |  |  |  |
| <b>12. DISTRIBUTION/AVAILABILITY STATEMENT</b><br>Approved for public release; distribution is unlimited.  |                    |                                   |                  |  |   |              |              |    |   |                                     |   |  |  |  |
| <b>13. SUPPLEMENTARY NOTES</b><br>N/A  |                    |                                   |                  |  |   |              |              |    |   |                                     |   |  |  |  |
| <b>14. ABSTRACT</b><br>Our overarching goal is to advance the cost-effective, appropriate use of geophysical technology in fractured rock. Specifically, we envision the FRGT-MST (1) equipping remediation professionals with a tool to understand what is likely to be realistic and cost effective when contracting geophysical services, and (2) reducing misguided, money-wasting applications of geophysical methods at sites where those methods are doomed to failure.   |                    |                                   |                  |  |   |              |              |    |   |                                     |   |  |  |  |
| <b>15. SUBJECT TERMS</b><br>DNAPL biodegradation characterization and monitoring, remediation, fractured rock aquifers.  |                    |                                   |                  |  |   |              |              |    |   |                                     |   |  |  |  |
| <b>16. SECURITY CLASSIFICATION OF:</b><br><table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 33%; padding: 2px;"><b>a. REPORT</b></td> <td style="width: 33%; padding: 2px;"><b>b. ABSTRACT</b></td> <td style="width: 33%; padding: 2px;"><b>c. THIS PAGE</b></td> </tr> <tr> <td style="text-align: center; padding: 2px;">Unclassified</td> <td style="text-align: center; padding: 2px;">Unclassified</td> <td style="text-align: center; padding: 2px;">UU</td> </tr> </table>   |                    |                                   | <b>a. REPORT</b> | <b>b. ABSTRACT</b>                             | <b>c. THIS PAGE</b>   | Unclassified | Unclassified | UU | <b>17. LIMITATION OF ABSTRACT</b><br><br>UL | <b>18. NUMBER OF PAGES</b><br><br>6 | <b>19a. NAME OF RESPONSIBLE PERSON</b><br><br><table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td style="padding: 2px;"><b>19b. TELEPHONE NUMBER (Include area code)</b></td> </tr> <tr> <td style="height: 20px;"></td> </tr> </table> |  | <b>19b. TELEPHONE NUMBER (Include area code)</b> |  |
| <b>a. REPORT</b>   | <b>b. ABSTRACT</b> | <b>c. THIS PAGE</b>               |                  |  |   |              |              |    |   |                                     |   |  |  |  |
| Unclassified   | Unclassified       | UU                                |                  |  |   |              |              |    |   |                                     |   |  |  |  |
| <b>19b. TELEPHONE NUMBER (Include area code)</b>   |                    |                                   |                  |  |   |              |              |    |   |                                     |   |  |  |  |
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## INTRODUCTION

Geophysical technologies have the potential to improve site characterization and monitoring in fractured rock, but the appropriateness and effectiveness of geophysics at a particular site depends strongly on project goals (e.g., identifying discrete fracture zones, mapping hydraulic properties, tracking contamination or remediation efforts, etc.) and site characteristics (e.g., lithology, depth to bedrock, presence of infrastructure). No method works at every site or for every goal. New approaches are needed to identify the set of geophysical methods appropriate to project goals, their likely effectiveness given site conditions, and practical cost considerations given project budget constraints. To this end, we present the Excel-based Fractured-Rock Geophysical Toolbox Method Selection Tool (FRGT-MST). Our overarching goal is to advance the cost-effective, appropriate use of geophysical technology in fractured rock. Specifically, we envision the FRGT-MST (1) equipping remediation professionals with a tool to understand what is likely to be realistic and cost effective when contracting geophysical services, and (2) reducing misguided, money-wasting applications of geophysical methods at sites where those methods are doomed to failure.

## APPROACH

The FRGT-MST is a user-friendly Excel-based software (**Figure 1**) for identification of the set of geophysical methods likely to be appropriate and effective for a given set of project goals based on site conditions. The ‘toolbox’ comprises 30 different geophysical methods divided into 4 categories: surface, cross-hole, borehole, and hydrologic. The user enters information in two tables (1) project and site parameters, including budget level; and (2) project goals (**Figure 2**). A third table is populated with indicators for whether each method could potentially support any of the specified goals, and whether each method is likely to work at the site described (**Figure 2**). The suite of potentially suitable methods is thus the intersection of the sets of appropriate and feasible methods.

Excel conditional formatting is used throughout the spreadsheet, coded based on simple rules of thumb and common-sense constraints for experiment design. For example:

- the feasibility of borehole optical televiewer requires that borehole fluids are not muddy/opaque;
- the feasibility of borehole radar requires that boreholes are open or PVC-cased; and
- the feasibility of crosshole methods with sufficient resolution generally requires well aperture (vertical:horizontal imaging area) >1.5.

Excel conditional formatting is also coded to identify which methods support specified project goals. For example,

- ERT is appropriate technology for time-lapse monitoring;
- surface seismic is appropriate technology for mapping depth to bedrock; and
- focused packer testing is appropriate technology for measuring small-scale hydraulic properties.

A series of 30 worksheet appendices are provided in the FRGT-MST, each with information on a different method from the toolbox (**Figure 3**). The appendices are hyperlinked from the table of methods in the FRGT MATRIX worksheet (**Figure 2**). Appendices provide basic information on the various

methods—a key reference and several graphics showing the instrumentation and (or) example results. The appendices are intended to provide overviews rather than in-depth information.

**FRGT METHOD SELECTION TOOL**

by F.D. Day-Lewis, C.D. Johnson, L.D. Slater, J.D. Robinson, D. Alarlagiannis, and C. L. Boyden

Contact info:  
<http://water.usgs.gov/logwbgas>

Last updated: 07/13/2015

*This program was designed to run in Excel Microsoft Office 2010*

**SUMMARY**  
 The Fractured Rock Geophysical Toolbox comprises a suite of geophysical methods for aquifer characterization and monitoring. This spreadsheet-based tool is designed to assist project managers and scientists in selecting tools that (1) satisfy study goals, and (2) are feasible for application at a given site, based on site characteristics as entered by the user.

**INSTALLATION**  
 Just use this spreadsheet. You may need to reset macro security to include the location of this file as a "trusted site." Go to "Excel Options" under the "Office Button." The spreadsheet is designed for use in Excel 2010 or later.

**INPUT**  
 The user must enter a site description and study goals using on the FRGT MATRIX worksheet using the numeric up-downs and menus provided.

**OUTPUT**  
 The spreadsheet will indicate the degree to which methods will be useful for satisfying project goals and which methods are likely feasible given the characteristics of the site.

**DISCLAIMER**  
 In our experience no one tool or single method achieves all goals when working in fractured-rock aquifers. We encourage a multi-disciplined approach that uses methods that measure different subsurface properties, thereby improving the detection, characterization, and interpretation of the aquifer. This FRGT utility is intended to help select methods and to assess their appropriateness and the potential for success given the goals of your investigation.  
 Results at any one site may vary depending on the actual tools and acquisition settings used. We recommend that when making tool selections you read the manuals or consult the vendors for the range of operation for each tool. The tools shown in the appendix are for descriptive purposes only and do not constitute an endorsement of any particular brand or tool.

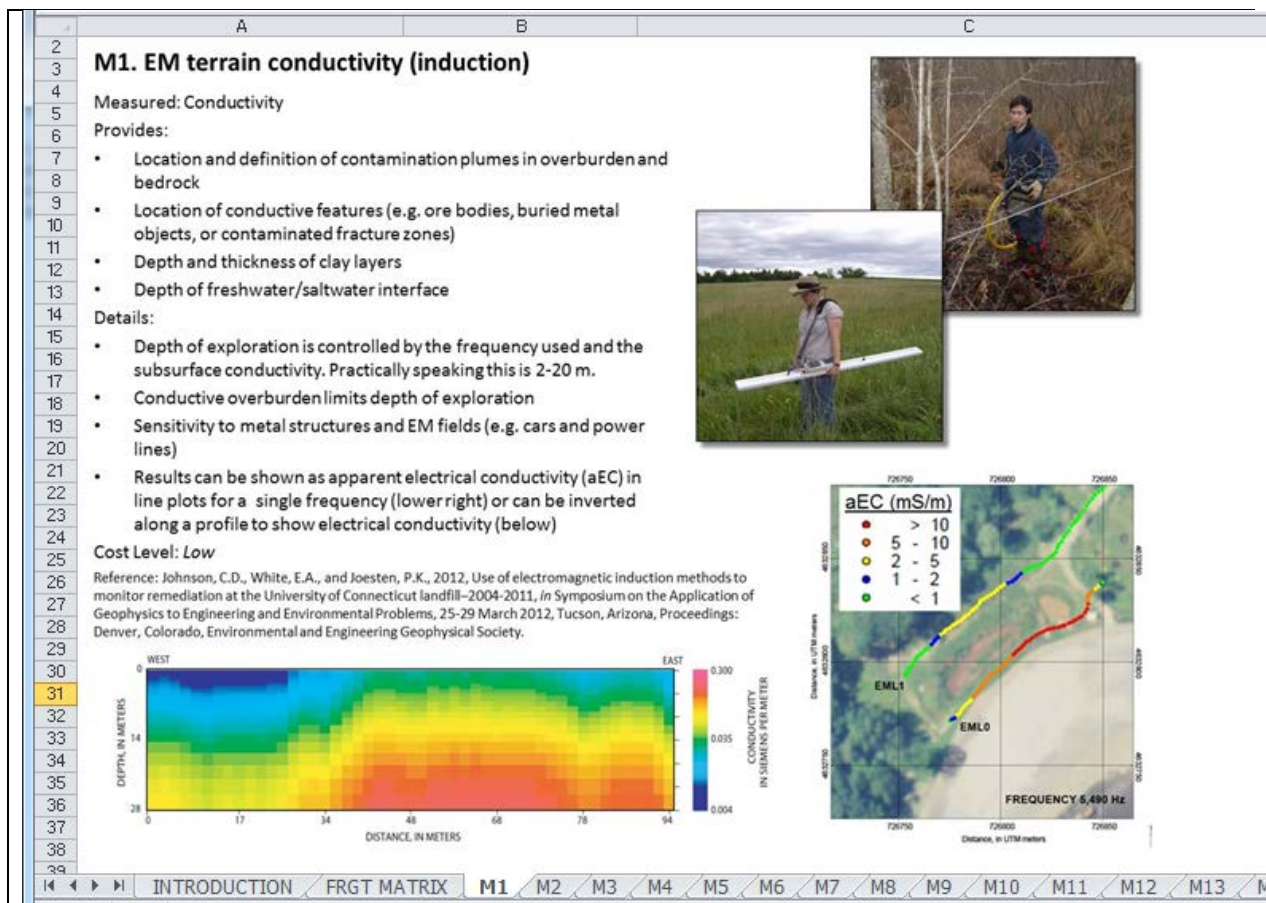
**ACKNOWLEDGMENTS**  
 Development of this tool was supported by the Environmental Security Technology Certification Program through grant ER-201118 and by the US Geological Survey Toxic Substances Hydrology Program.

INTRODUCTION FRGT MATRIX M1 M2 M3 M4 M5 M6 M7 M8 M9 M10 M11 M12 M13 M14 M15 M16 M17

**Figure 1.** FRGT INTRODUCTION worksheet which provides background information and instructions for the use of the FRGT-MST.

| FRGT METHOD SELECTION TOOL  |  |  |  |   |  |  |  |   |  |  |  | USGS<br>science for a changing world   |  | RUTGERS<br>Environmental Social Technology Center |  |   |  |  |  |
|---|--|--|--|---|--|--|--|---|--|--|--|--|--|---|--|---|--|--|--|
| Fill in cells shaded aqua-blue (in column D). All other cells will be automatically updated. <span style="float: right;"> <input checked="" type="radio"/> Indicates method is potentially suitable<br/> <input type="radio"/> Indicates method is likely not suitable<br/> <input checked="" type="radio"/> Indicates method is likely appropriate/effective<br/> <input type="radio"/> Indicates method is not likely appropriate/effective         </span>   |  |  |  |   |  |  |  |   |  |  |  |  |  |   |  |   |  |  |  |
| <b>Project and site parameters</b><br>1. What is the depth to bedrock (m)? 15<br>2. What is the electrical resistivity of bedrock (ohm-m)? 500<br>3. What is the minimum spacing between wells (m)? 4<br>4. What is the well casing? Open<br>5. What is the vertical extent of open holes (m)? 50<br>6. Is borehole fluid turbid/muddy (opaque)? Yes<br>7. Borehole diameter (inches) 6<br>8. Cultural EM interference? (utilities, pipes, etc.) Yes<br>9. Is it possible to disturb the ground for electrodes or geodes? Yes<br>10. What is native groundwater conductivity (micro-S/cm)? 150<br>11. What is the project cost threshold for a given method? Medium |  |  |  | <b>Methods</b><br><b>Appropriate for goals</b><br><b>Effectiveness at site</b><br><b>Relative cost</b><br><b>Method contributes to goal:</b><br><b>Made infeasible by site parameter:</b>   |  |  |  | <b>Method contributes to goal:</b><br><b>Made infeasible by site parameter:</b>   |  |  |  |  |  |   |  |   |  |  |  |
| <b>Goals</b><br>A. Identify discrete fracture network characteristics No<br>B. Identify lithologic contacts No<br>C. Map depth to bedrock No<br>D. Understand large-scale anisotropy, average fracture cov. No<br>E. Estimate discrete fracture hydraulic properties Yes<br>F. Estimate small-scale effective hydraulic properties Yes<br>G. Estimate large-scale hydraulic properties Yes<br>H. Identify interval hydraulic connections Yes<br>I. Time-lapse snapshots of amendment delivery Yes<br>J. Continuous monitoring of degradation No<br>K. Screening for iron minerals No  |  |  |  | <b>Surface methods</b><br>1. EM terrain conductivity (induction) <input checked="" type="radio"/> <input checked="" type="radio"/> Low<br>2. ERT <input checked="" type="radio"/> <input checked="" type="radio"/> Low<br>3. GPR <input checked="" type="radio"/> <input checked="" type="radio"/> Low<br>4. Resistivity - azimuthal <input checked="" type="radio"/> <input checked="" type="radio"/> Low<br>5. SP - azimuthal <input checked="" type="radio"/> <input checked="" type="radio"/> Low<br>6. Seismic refraction <input checked="" type="radio"/> <input checked="" type="radio"/> Low<br>7. Seismic reflection <input checked="" type="radio"/> <input checked="" type="radio"/> Medium<br>8. Time-domain EM <input checked="" type="radio"/> <input checked="" type="radio"/> Low |  |  |  | <b>Cross-hole methods</b><br>9. ERT <input checked="" type="radio"/> <input checked="" type="radio"/> Medium<br>10. GPR <input checked="" type="radio"/> <input checked="" type="radio"/> High<br>11. IP <input checked="" type="radio"/> <input checked="" type="radio"/> Medium<br>12. Seismic <input checked="" type="radio"/> <input checked="" type="radio"/> High |  |  |  | <b>Borehole methods</b><br>13. ATV <input checked="" type="radio"/> <input checked="" type="radio"/> Low<br>14. Caliper <input checked="" type="radio"/> <input checked="" type="radio"/> Low<br>15. EM induction <input checked="" type="radio"/> <input checked="" type="radio"/> Low<br>16. Flowmeter (single hole) <input checked="" type="radio"/> <input checked="" type="radio"/> Low<br>17. Flowmeter (cross-hole) <input checked="" type="radio"/> <input checked="" type="radio"/> Low<br>18. Damu <input checked="" type="radio"/> <input checked="" type="radio"/> Low<br>19. IP and Normal Resistivity <input checked="" type="radio"/> <input checked="" type="radio"/> Low<br>20. Magnetic susceptibility <input checked="" type="radio"/> <input checked="" type="radio"/> Low<br>21. NMR <input checked="" type="radio"/> <input checked="" type="radio"/> Medium<br>22. OTV <input checked="" type="radio"/> <input checked="" type="radio"/> Low<br>23. Radar (borehole GPR) <input checked="" type="radio"/> <input checked="" type="radio"/> Medium<br>24. Video camera <input checked="" type="radio"/> <input checked="" type="radio"/> Low |  |   |  | <b>Hydrologic tests</b><br>25. Dilution/Fluid replacement <input checked="" type="radio"/> <input checked="" type="radio"/> High<br>26. Focused packet testing <input checked="" type="radio"/> <input checked="" type="radio"/> High<br>27. Fluid resistivity & temperature <input checked="" type="radio"/> <input checked="" type="radio"/> Low<br>28. High resolution temperature <input checked="" type="radio"/> <input checked="" type="radio"/> High<br>29. Open-hole hydraulic tests <input checked="" type="radio"/> <input checked="" type="radio"/> Medium<br>30. Tracer tests <input checked="" type="radio"/> <input checked="" type="radio"/> High |  |  |  |
| <b>Assumptions</b><br>- Wells are partially or completely fluid filled  |  |  |  | This FRGT utility is intended to help select methods and to assess their appropriateness and the potential for success given the goals of your investigation. Actual performance of the geophysical and hydraulic tools may vary depending on the specific tool used and acquisition settings.  |  |  |  |   |  |  |  |  |  |   |  |   |  |  |  |
| <b>Comments</b>   |  |  |  |   |  |  |  |   |  |  |  |  |  |   |  |   |  |  |  |

**Figure 2.** FRGT MATRIX worksheet, where the user enters project/site parameters and goals and the output table is generated showing which methods are likely feasible for the site and appropriate to specified goals. Method satisfying both feasibility and appropriateness conditions are indicated by 'green lights' in column F, whereas methods that are infeasible or inappropriate are indicated by 'red lights.'





| FRGT METHOD SELECTION TOOL  |  |  |  |  |  |  |  |   |  |  | USGS<br>science for a changing world |  | RUTGERS<br>Environmental Science Technology Center Program |  |
|---|--|--|--|--|--|--|--|---|--|--|--------------------------------------|--|--|--|
| Fill in cells shaded aqua-blue (in column D). All other cells will be automatically updated. <span style="float: right;"> <input checked="" type="radio"/> indicates method is potentially suitable<br/> <input type="radio"/> indicates method is likely not suitable<br/> <input checked="" type="radio"/> indicates method is likely appropriate/effective<br/> <input type="radio"/> indicates method is not likely appropriate/effective         </span>   |  |  |  |  |  |  |  |   |  |  |                                      |  |  |  |
| <b>Project and site parameters</b><br>1. What is the depth to bedrock (m)? 15<br>2. What is the electrical resistivity of bedrock (ohm-m)? 100<br>3. What is the minimum spacing between wells (m)? 4<br>4. What is the well casing? Open<br>5. What is the vertical extent of open holes (m)? 20<br>6. Is borehole fluid turbid/muddy (opaque)? No<br>7. Borehole diameter (inches) 6<br>8. Cultural EM interference? (utilities, pipes, etc.) Yes<br>9. Is it possible to disturb the ground for electrodes or geophones? Yes<br>10. What is native groundwater conductivity (micro-S/cm)? 150<br>11. What is the project cost threshold for a given method? High |  |  |  | <b>Methods</b><br><b>Surface methods</b><br>1. EM terrain conductivity (induction) <input checked="" type="radio"/> <input type="radio"/> Low<br>2. ERT <input checked="" type="radio"/> <input type="radio"/> Low<br>3. GPR <input checked="" type="radio"/> <input type="radio"/> Low<br>4. Resistivity - azimuthal <input checked="" type="radio"/> <input type="radio"/> Low<br>5. SP - azimuthal <input checked="" type="radio"/> <input type="radio"/> Low<br>6. Seismic refraction <input checked="" type="radio"/> <input type="radio"/> Medium<br>7. Seismic reflection <input checked="" type="radio"/> <input type="radio"/> Low<br>8. Time domain EM <input checked="" type="radio"/> <input type="radio"/> Low<br><b>Cross-hole methods</b><br>9. ERT <input checked="" type="radio"/> <input type="radio"/> Medium<br>10. GPR <input checked="" type="radio"/> <input type="radio"/> High<br>11. IP <input checked="" type="radio"/> <input type="radio"/> Medium<br>12. Seismic <input checked="" type="radio"/> <input type="radio"/> High<br><b>Borehole methods</b><br>13. ATV <input checked="" type="radio"/> <input type="radio"/> Low<br>14. Caliper <input checked="" type="radio"/> <input type="radio"/> Low<br>15. EM induction <input checked="" type="radio"/> <input type="radio"/> Low<br>16. Flowmeter (single hole) <input checked="" type="radio"/> <input type="radio"/> Low<br>17. Flowmeter (cross-hole) <input checked="" type="radio"/> <input type="radio"/> Low<br>18. Gamma <input checked="" type="radio"/> <input type="radio"/> Low<br>19. IP and Normal Resistivity <input checked="" type="radio"/> <input type="radio"/> Low<br>20. Magnetic susceptibility <input checked="" type="radio"/> <input type="radio"/> Low<br>21. NMR <input checked="" type="radio"/> <input type="radio"/> Medium<br>22. OTV <input checked="" type="radio"/> <input type="radio"/> Low<br>23. Badger (borehole GPR) <input checked="" type="radio"/> <input type="radio"/> Medium<br>24. Video camera <input checked="" type="radio"/> <input type="radio"/> Low<br><b>Hydrologic tests</b><br>25. Dilution/fluid replacement <input checked="" type="radio"/> <input type="radio"/> High<br>26. Focused packer testing <input checked="" type="radio"/> <input type="radio"/> High<br>27. Fluid resistivity & temperature <input checked="" type="radio"/> <input type="radio"/> Low<br>28. High resolution temperatures <input checked="" type="radio"/> <input type="radio"/> High<br>29. Open-hole hydraulic tests <input checked="" type="radio"/> <input type="radio"/> Medium<br>30. Tracer tests <input checked="" type="radio"/> <input type="radio"/> High |  |  |  | <b>Method contributes to goal:</b><br>A B C D E F G H I J K |  | <b>Made infeasible by site parameter:</b><br>1 2 3 4 5 6 7 8 9 10 11 |                                      |  |  |  |
| <b>Goals</b><br>A. Identify discrete fracture network characteristics Yes<br>B. Identify lithologic contacts Yes<br>C. Map depth to bedrock No<br>D. Understand large-scale anisotropy, average fracture connectivity No<br>E. Estimate discrete fracture hydraulic properties Yes<br>F. Estimate small-scale effective hydraulic properties No<br>G. Estimate large-scale hydraulic properties No<br>H. Identify interval hydraulic connections Yes<br>I. Time-lapse snapshots of amendment delivery Yes<br>J. Continuous monitoring of degradation No<br>K. Screening for iron minerals No  |  |  |  |  |  |  |  |   |  |  |                                      |  |  |  |
| <b>Assumptions</b><br>- Walls are partially or completely fluid filled  |  |  |  |  |  |  |  |   |  |  |                                      |  |  |  |
| <b>Comments</b><br>- May require the use of a borehole liner.   |  |  |  |  |  |  |  |   |  |  |                                      |  |  |  |
| This FRGT utility is intended to help select methods and to assess their appropriateness and the potential for success given the goals of your investigation. Actual performance of the geophysical and hydrologic tools may vary depending on the specific tool used and acquisition settings.   |  |  |  |  |  |  |  |   |  |  |                                      |  |  |  |

**Figure 4.** FRGT Matrix with inputs and output for the U.S. Geological Survey research site at the Naval Air Warfare Center in West Trenton, NJ.

## DISCUSSION AND LIMITATIONS

We encourage users to look at the equations used throughout the spreadsheet to gain insight into experiment-design parameters and the potential uses of various methods. We stress that the FRGT-MST is, necessarily, a simple tool and like any tool, its capabilities are limited. The results of the spreadsheet analyses are not the official recommendations of USGS or Rutgers. The USGS and Rutgers provide no warranty, expressed or implied, as to the correctness of the furnished software or the suitability for any purpose. The software has been tested, but as with any complex software, there could be undetected errors. Users who find errors are requested to report them to the Dr. Frederick Day-Lewis (USGS) at [daylewis@usgs.gov](mailto:daylewis@usgs.gov).

## AKNOWLEDGMENTS

The development of the FRGT-MST was supported by ESTCP grant ER-201118.